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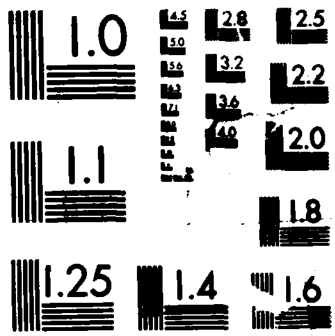
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19. ABSTRACT

Innovative techniques for obtaining particle size and velocity are being investigated. The four methods are: phase Doppler, ratiometric light scatter detection, Lagrangian frame particle analyzer, and scattered light heterodyne interferometry. Although these methods have overlapping capabilities, each offers additional possibilities for providing heretofore unavailable data. The phase Doppler method has been highly refined and provides reliable particle size and velocity measurements. However, research has been required on the light scattering mechanisms due to nonuniform particle illumination and the sampling statistics. Discrepancies between the light scattering theory and experimental observations have required the expansion of the theory to include the affects of nonuniform illumination. Under certain conditions, the detection of refracted light where none is predicted, remains as a question to be resolved. These questions apply to all of the methods addressed. However, the ratiometric techniques may be used in the on-axis forward scatter light detection mode. This will allow the measurement of irregular-shaped particles moving at high speed using light configuration, the system is limited to dilute particle fields. Currently, the theoretical analysis and optical configuration have been completed and preliminary tests have shown that the basic concept will work. Interests in turbulent dispersion of spray drops suggested the need for measuring the particle dynamics in a Lagrangian frame. The method described promises to provide tracking of individual drops and measuring their local size and velocity. Array detectors are being investigated to provide adequate speed, sensitivity, and spatial resolution. The transmitter optics have been defined. Finally, to exploit the significant advantages of the light scattering interferometry method, a heterodyne configuration has been proposed that may allow processing at much higher particle speeds. Only preliminary analyses of the method have been completed during this first year of the program.

RESEARCH OBJECTIVES

The following is an outline of the research objectives addressed in the program:

1. Perform analyses on the particle number density limitations and predict the measurement effects of multiple particles in the sample volume of the phase/Doppler system.

2. Conduct experiments on irregular-shaped and opaque particles to define the phase/Doppler instrument response to these particles. Also consider inhomogeneous (slurry) drops to define the effects of particle morphology on the measurements.

3. Generate software and conduct experiments to determine the affect of velocity biasing and evaluate the accuracy of the McLaughlin-Tiederman correction.

4. Investigate the conditions associated with phase/Doppler measurements of gas phase turbulence parameters in a polydispersed two-phase flow. In particular, investigate and develop methods for overcoming errors due to particle concentration biasing.

5. Generate a complete theoretical description of the proposed heterodyne concept.

6. Test the scattered light heterodyne interferometry method using a breadboard optical system performance, stability, and alignment requirements.

7. Investigate the use of electro-optical modulators (EOM) for maintaining the scattered light heterodyne interferometer system in quadrature and for processing speed.

8. Evaluate the scattered light heterodyne interferometry method in the measurement of dense sprays and perform tests in reacting flows to quantify the effects of turbulence-induced refractive index fluctuations.

9. Perform measurements comparing scattered light heterodyne interferometry with the phase/Doppler method.

10. Perform light scattering calculations using the Mie theory to define the ratiometric intensity detection instrument response.

11. Complete the theoretical decription of ratiometric intensity detection including the probe volume.

12. Set up breadboard ratiometric intensity detection optical system and prove the feasibility of the method.

13. Perform measurements comparing ratiometric intensity detection with the phase/Doppler instrument.

14. Evaluate the ratiometric intensity detection method in high speed and reacting sprays.

15. Perform an analysis on the intensity and sweep rates required for Langrangian frame measurements in typical spray drop measurements.

16. Evaluate various fluorescein dyes for application to drop tracking and determine the light intensities required for adequate signal-to-noise ratio.

17. Set up a breadboard optical system for the experimental Langrangian frame evaluations.

18. Perform experiments using monodisperse drop streams to assess the detectability and tracking capability of the

Langrangian frame method.

19. Conduct experiments with fluorescein dye drops injected into a polydisperse spray and measure the drop angle of trajectory and velocity at sequential points as it passes through the spray.

20. Characterize the turbulent dispersion behavior of drops in a turbulent two-phase flow.

STATUS OF THE RESEARCH EFFORT

The general area of research treats the problem of measuring the size and velocity of particles in practical combustor environments. In the present program, four innovative light scatter detection methods are undergoing investigations to determine their suitability for providing unique particle field characterizations. Research on these methods will lead to a complete range of measurement capabilities including relatively dense sprays, combusting sprays, irregular particles formed as products, high speed sprays, and turbulent dispersion of drop clusters. Reliable measurements in turbulent two-phase flows is also a major goal of this program. This report will cover the work and progress during the first year of this program.

Phase Doppler Particle Analyzer (PDPA)

Having undergone a significant development effort, the phase Doppler method has led to a viable instrument for measuring the size and velocity of spherical particles in turbulent flows. However, a number of critical research questions remain to be answered before reliable and accurate measurements can be made in highly turbulent two-phase flows. These problems are associated with the need to obtain measurements in dense sprays and the effects of velocity and concentration gradient biasing.

Measurements in dense sprays using single particle counter (spc) methods require a low probability that more than one particle passes the sample volume at a time. This can be achieved by reducing the sampling volume size. However, the characteristics of the light scattering place limitations on the minimum focused beam diameter that can be used for a given particle size range. First of all, off-axis light scatter detection is necessary for spc's to operate in relatively dense sprays. As such, the light scattering is predominantly by refraction and reflection, depending upon the angle of detection. When the particle is on the order of the Gaussian beam diameter incident upon it, the dominant light scattering component can depend upon the trajectory through the beam, figure 1. Although the scattering coefficient for refraction is approximately 80 times that for reflection, on certain trajectories the light scattered by reflection can be of similar order. Reflection scatter can produce very large errors when it is not the expected scattering component.

Significant effort has been devoted to eliminating this troublesome error source. The first approach was to develop logic and the use of redundant measurements to eliminate the problem. This approach was approximately 90% effective but under severe conditions and with the focused beam waist on the order of the largest drop measured, on the order of 10 drops out of 10,000 can be erroneously measured as large drops throwing off Sauter Mean Diameter (D_{32}) and Volume Mean Diameter (D_{30}).

Hence, an additional approach using the signal amplitude to reject these large errors has been incorporated. This method sets a bandwidth on the scattering amplitudes within which signals will be accepted. The approach has the added advantage of providing a better definition of the sampling volume and providing the information for automatically setting the detector gains. Current testing of the method indicates that after some further refinement, it will essentially eliminate the remaining error.

Concern with measuring fuel sprays during combustion has led to some concern over the uncertainty with the refractive index. The refractive index may change as the more volatile components evaporate. To eliminate this concern, further investigations using reflective scattering which results in measurements that are independent of refractive index were conducted. With the proper incident polarization, light scattering between approximately 60° to 120° is dominated by, if not entirely due to reflection. For example at 120°, the scattering should be by pure reflection. This opens the significant possibility of using a focused beam diameter that is much smaller than the largest drop to be measured which will form a very small sample volume and potentially provide an approved signal-to-noise ratio. At the same time, the upper limit on drop number density can be extended. Finally, reflected light can be used to measure alternate fuel drops composed of slurries or emulsions.

Velocity and particle concentration biasing remains as a problem in measuring gas and dispersed phase velocities in turbulent flows. Recent solutions of these problems by Nejad et al. and Gould et al. have used uniform time interval sampling techniques. With this method, the actual particle rate must be at least ten times greater than the quasi-uniform sampling rate. This tends to remove the correlation of sampling rate with velocity and/or concentration. The method has two serious disadvantages; the data rate is reduced by at least an order of magnitude and the particle number density information is lost. Our approach is to obtain measurements of the particle size, velocity, and time-of-arrival. The correlation between particle time-of-arrival and velocity will be generated to obtain a mapping of the particle arrivals with fluctuating velocities. These results will then be analyzed to determine how this bias can be removed from the sampling statistics. In the case of concentration biasing, the same information can be used to normalize the readings to eliminate the bias that occurs when velocity excursions from regions of higher concentrations produce a corresponding increased sampling rates. Our method has the advantage of fully utilizing all of the signals and will allow the determination of the time-varying number density.

Hardware needed to acquire these measurements is in place and the software is nearing completion. Data acquisition and analysis will begin within two months.

Ratiometric Particle Analyzer

The necessary theoretical analysis for the method has been completed. Particle size, speed, number density and flux should be measurable with the method. Figure 2 shows the basic optic configuration. The method promises to provide measurements of irregular, as well as spherical particles moving at high speeds. At moderate to low number densities, the maximum speed can be as high as 1,000 m/sec.

Optics have been set up on our laboratory breadboard, and preliminary signal analysis has shown that the method will work. A high speed electronics signal processor has been developed (under Aerometrics' funding) to acquire data for these evaluations. Software is being written (under Aerometrics' funding) to efficiently manage the data and to expedite the detailed analysis of the method. The software will be completed within the next three months, after which an extensive series of tests will be conducted to evaluate the method and define its performance limits.

Lagrangian Frame Drop Dynamics Analyzer

Work is just starting on this method illustrated in figure 3. The method promises to track and determine the local velocity of individual drops as they pass through a turbulent flow field. Basic analyses have been conducted to establish the optical parameters requred, and hence, the optical system.

Currently, fluorescein and other fluorescent materials are being tested for tagging the drops. Monodispersed streams of dye drops are being used to establish detectability thresholds and the possibility of simultaneously sizing the drops. Sizing the drops can be accomplished with coaxial beams similar to the Ratiometric method. Elongated beam profiles may be required to allow detection of drops that wander out of the plane of motion circumscribed by the beams.

CCD array detectors are being researched for use in the receiver system. Consultation with R. Hanson and co-workers at Stanford who have extensive experience with these devices will ensure that the best possible system is acquired.

Future work will entail the acquisition of the hardare components and construction of the breadboard optical system.

Scattered Light Heterodyne Interferometry

There was no activity on the investigation of this method during the past year. Work will start on this method in approximately six months.

Summary and Forecast

The research is proceeding as planned. No changes in personnel or research objectives are expected in the coming year.

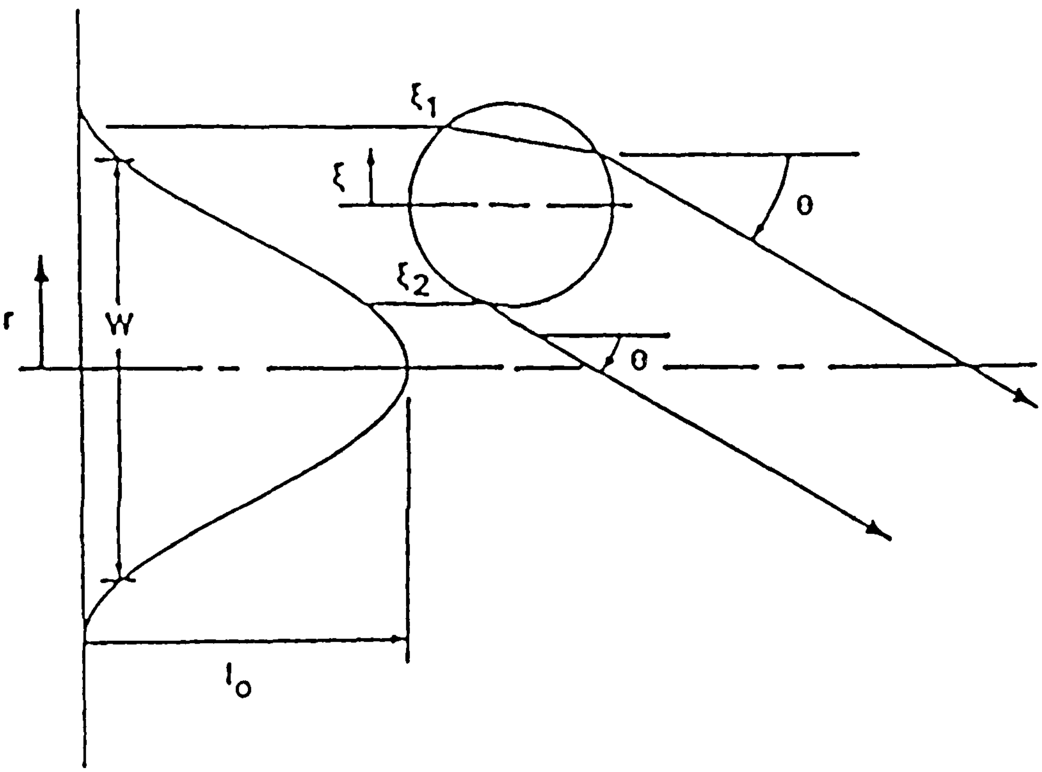

Figure 1. Schematic showing the Gaussian intensity beam incident upon a sphere.

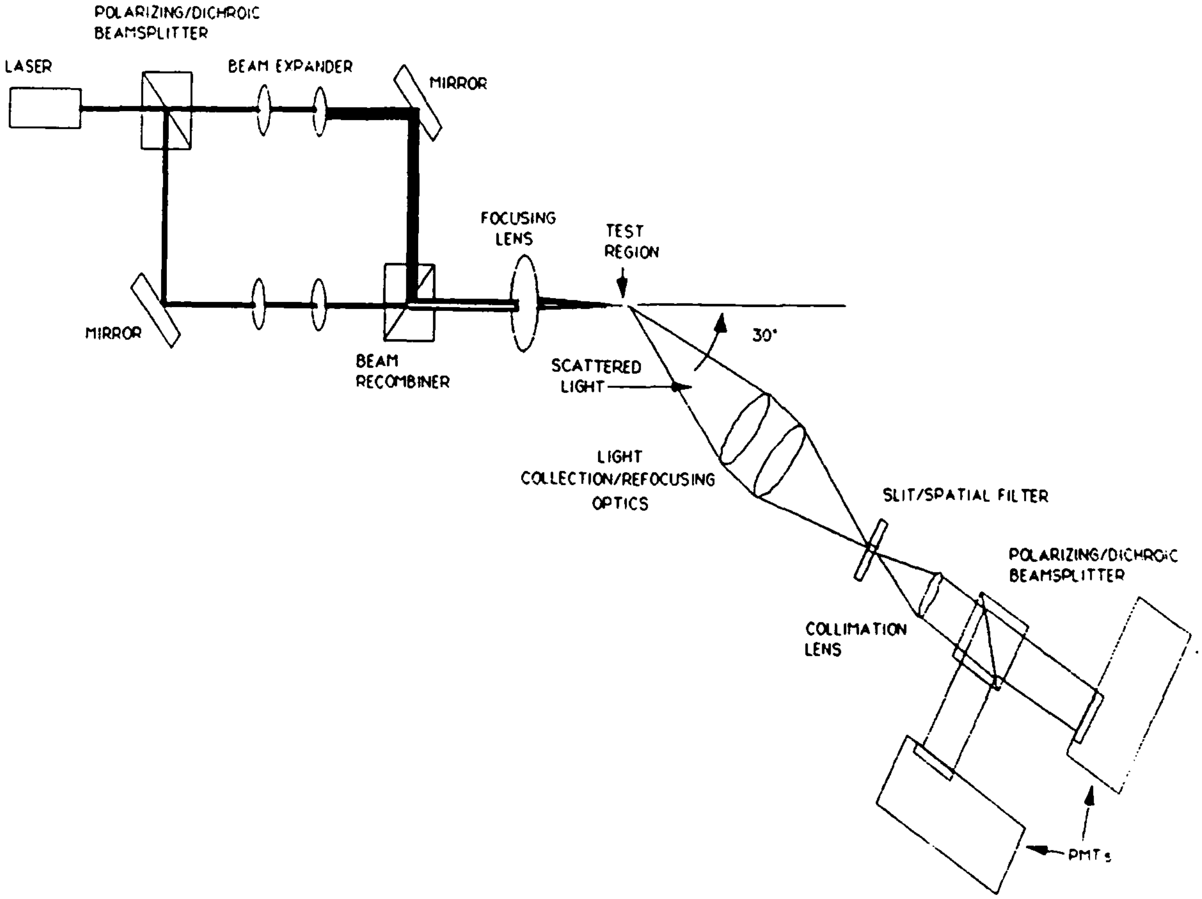

Figure 2. Ratiometric particle analyzer optical configuration.

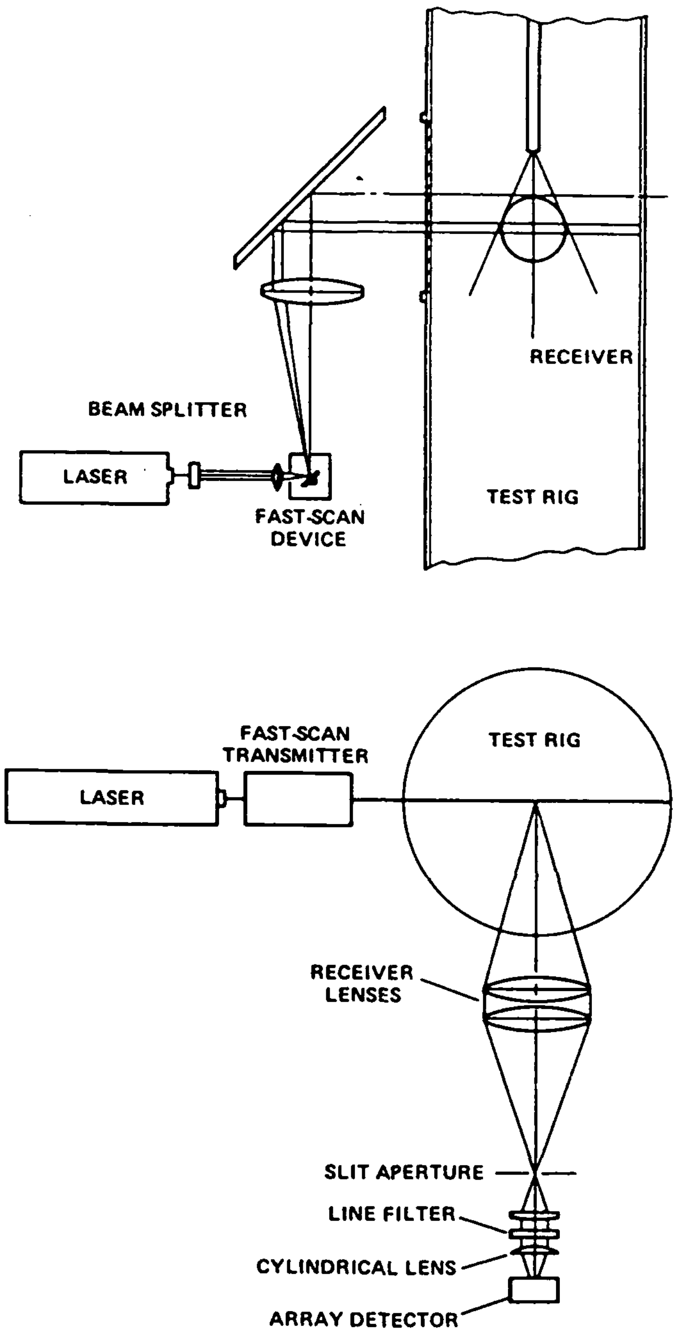

Figure 3. Schematic of the Fast-Scan particle analyzer.

Personnel on the Program

1. Dr. William D. Bachalo, Senior Scientist

2. Mr. Michael J. Houser, Scientist

3. Mr. James N. Smith, Scientist

PUBLICATIONS

1. W. D. Bachalo, M. J. Houser, and J. N. Smith, "Behavior of Sprays Produced by Pressure Atomizers as Measured Using the Phase Doppler Instrument," Atomization and Spray Technology, Vol 3, 1987.

2. W. D. Bachalo, R. C. Rudoff, and M. J. Houser, "Laser Velocimetry in Turbulent Flow Fields: Particle Response," AIAA-87-0118, to be submitted to AIAA Journal.

3. R. C. Rudoff, M. J. Houser, and W. D. Bachalo, "Experiments on Spray Interactions in the Wake of a Bluff Body," to appear in the Journal of Engineering for Gas Turbines and Power.

4. B. W. Young and W. D. Bachalo, "The Direct Comparison of Three 'In-Flight' Droplet Sizing Techniques for Pesticide Spray Research," to be submitted to the Journal of Aerosol Science.

5. W. D. Bachalo, "Method and Apparatus to Determine the Size and Velocity of Particles Using Polarized Laser Light," U.S. Patent Disclosure, 01410.913.

INTERACTIONS

1. W. D. Bachalo and M. J. Houser, "An Instrument for Two-Component Velocity and Particle Size Measurement," 3rd International Symposium on Applications of Laser Anemometry to Fluid Mechanics, Lisbon, Portugal, July 1986.

2. W. D. Bachalo, "A Review of Aero-Optical Measurements and Interpretation," SPIE, San Diego, July 1986.

3. W. D. Bachalo, (Invited), "Interferometric Single Particle Sizing Methods," ICALEO'86, Arlington, Virginia, November 1986.

4. W. D. Bachalo, R. C. Rudoff, and M. J. Houser, "Laser Velocimetry in Turbulent Flow Fields: Particle Response," AIAA 87-0118, 25th Aerospace Sciences Meeting, Reno, Nevada, January, 1987.

5. R. C. Rudoff, M. J. Houser, and W. D. Bachalo, "Two-Phase Flow Measurements of a Spray in a Turbulent Flow," AIAA 87-0062, 25th Aerospace Sciences Meeting, Reno, Nevada, January, 1987.

6. W. D. Bachalo, "Research on Turbulent Two-Phase Flows," Seminar, University of Illinois, Chicago, February, 1987.

7. W. D. Bachalo, "Applications of the Phase Doppler Particle Analyzer," Seminar, University of Wisconsin, Madison, February, 1987.

8. W. D. Bachalo, "Diagnostics for Two-Phase Flow Research," Seminar, University of Cairo, Egypt, April, 1987.

9. W. D. Bachalo, "Spray Diagnostics and Applications to Industrial Power Plants," Seminar, ENEL, Pisa, Italy, April, 1987.

10. W. D. Bachalo, "The Phase Doppler Method: Analysis and Application," International Symposium on Optical Particle Sizing: Theory and Practice," I.N.S.A. de Rouen, France, May, 1987.

11. B. W. Young and W. D. Bachalo, "The Direct Comparison of Three 'In-Flight' Droplet Sizing Techniques for Pesticide Spray," I.N.S.A. de Rouen, France, May, 1987.

12. W. D. Bachalo, "Particle Response in Turbulent Two-Phase Flows," The Uses of Computers in Laser Velocimetry, ISL, Saint Louis, France, May, 1987.

13. R. C. Rudoff, M. J. Houser, and W. D. Bachalo, "Two-Phase Measurements of a Spray in the Wake of a Bluff Body," presented at the 8th International Symposium on Air Breathing Engines, Cincinnati, Ohio, June, 1987.

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